

Novel universality and Higgs decay $H \rightarrow \gamma\gamma, gg$ in the $SO(5) \times U(1)$ gauge-Higgs unification

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Abstract

The $SO(5) \times U(1)$ gauge-Higgs unification in the Randall-Sundrum warped space with the Higgs boson mass $m_H = 126$ GeV is constructed. An universal relation is found between the Kaluza-Klein (KK) mass scale m_{KK} and the Aharonov-Bohm (AB) phase θ_H in the fifth dimension; $m_{KK} \sim 1350 \text{ GeV}/(\sin \theta_H)^{0.787}$. The cubic and quartic self-couplings of the Higgs boson become smaller than those in the standard model (SM), having universal dependence on θ_H . The decay rates $H \rightarrow \gamma\gamma, gg$ are evaluated by summing contributions from KK towers. Corrections coming from KK excited states are finite and about 0.2% (2%) for $\theta_H = 0.12$ (0.36), branching fractions of various decay modes of the Higgs boson remaining nearly the same as in the SM. The signal strengths of the Higgs decay modes relative to the SM are $\sim \cos^2 \theta_H$. The mass of the first KK Z is predicted to be 5.9 (2.4) TeV for $\theta_H = 0.12$ (0.36). We also point out the possible enhancement of $\Gamma(H \rightarrow \gamma\gamma)$ due to the large $U(1)_X$ charge of new fermion multiplets.

With the discovery of a Higgs-like boson at LHC [1, 2] it is emergent to pin down its properties to see if it is the Higgs boson in the standard model (SM). The mechanism of electroweak (EW) symmetry breaking is at issue. It is not clear if the EW symmetry is spontaneously broken in a way described in the SM. The mass of the discovered boson is about 126 GeV. Its couplings to other fields, however, may or may not be the same as in the SM. The excess in the decay mode $H \rightarrow \gamma\gamma$ has been reported, though more data are necessary for the issue to be settled. [3, 4]

Many alternative mechanisms for the EW symmetry breaking have been proposed with new physics beyond the SM. Supersymmetry with a light Higgs boson has been a popular scenario in the past, though no evidence has been found so far. It has been discussed that the value $m_H = 126$ GeV can lead to the direct connection to physics at the Planck scale through the vacuum stability of the SM or conformality.[5]-[7] Many scenarios have been proposed to account for the apparent excess rate for the Higgs decay to two photons at LHC.[8]-[16]

The gauge-Higgs unification scenario is one of the models with new physics at the TeV scale, in which the 4D Higgs boson is identified with the zero mode of the extra-dimensional component of the gauge fields.[17]-[19] In this paper we show that the value of the Higgs boson mass $m_H = 126$ GeV has profound implications in the gauge-Higgs unification. We evaluate the decay rates $H \rightarrow \gamma\gamma, gg$ by summing contributions from all Kaluza-Klein (KK) excited states of the W boson and fermions in the internal loops. Surprisingly there arises no divergence associated with the infinite sum, thanks to destructive interference in the amplitude. The corrections to the decay rates $H \rightarrow \gamma\gamma, gg$ are finite and small, being independent of a cutoff scale. With $m_H = 126$ GeV as an input, the deviation of the branching fractions of the H decay from the values in the SM is found to be 2% or less.

In the $SO(5) \times U(1)$ gauge-Higgs unification model [20] the 4D neutral Higgs field appears as 4D fluctuations of the AB, or Wilson line, phase θ_H along the fifth dimension in the Randall-Sundrum (RS) warped space-time. In the minimal model with quark and lepton multiplets in the vector representation of $SO(5)$ [21, 22] the effective potential $V_{\text{eff}}(\theta_H)$ is minimized at $\theta_H = \pm\frac{1}{2}\pi$, where the Higgs boson becomes absolutely stable.[23] This is due to the emergence of the H parity invariance.[24] To have an unstable Higgs boson with a mass $m_H = 126$ GeV the model need to be modified by breaking the H parity. Further in the minimal model the consistency with the electroweak precision measurements requires a large warp factor z_L , which typically leads to a larger value $m_H \sim 135$ GeV.[25] The Higgs mass can be made smaller in the supersymmetric version of the model.[26]

To solve these problems we introduce n_F fermion multiplets, Ψ_F , in the spinor representation of $SO(5)$ in the model specified in Ref. [22]. The metric of the RS is given by $ds^2 = e^{-2\sigma(y)}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$ where $\sigma(y) = k|y|$ for $|y| \leq L$ and $\sigma(y + 2L) = \sigma(y)$. The warp factor is $z_L = e^{kL} \gg 1$. Ψ_F satisfies the boundary conditions $\Psi_F(x, -y) = \gamma_5 P \Psi_F(x, y)$ and $\Psi_F(x, L - y) = -\gamma_5 P \Psi_F(x, L + y)$ where $P = \text{diag}(1, 1, -1, -1)$ acts on $SO(5)$ spinor indices. Then the mass spectrum $m_n = k\lambda_n$ of the KK tower of Ψ_F is determined by $S_L(1; \lambda_n, c_F)S_R(1; \lambda_n, c_F) + \cos^2 \frac{1}{2}\theta_H = 0$. Here $S_{L,R}(z; \lambda, c) = \mp \frac{1}{2}\pi\lambda\sqrt{zz_L}F_{c\pm(1/2), c\pm(1/2)}(\lambda z, \lambda z_L)$, where the upper (bottom) sign refers to L (R). $F_{\alpha,\beta}(u, v) = J_\alpha(u)Y_\beta(v) - Y_\alpha(u)J_\beta(v)$ where J_α, Y_α are Bessel functions. It has been shown that all 4D anomalies in the model of Ref. [22] cancel. This property is not spoiled by the addition of Ψ_F multiplets, as 4D fermions of Ψ_F are vectorlike.

The effective potential $V_{\text{eff}}(\theta_H)$ is cast in a simple form of an integral. The relevant part of $V_{\text{eff}}(\theta_H)$ is given by

$$\begin{aligned}
V_{\text{eff}}(\theta_H; \xi, c_t, c_F, n_F, k, z_L) &= 2(3 - \xi^2)I[Q_W] + (3 - \xi^2)I[Q_Z] + 3\xi^2 I[Q_S] \\
&\quad - 12\{I[Q_{\text{top}}] + I[Q_{\text{bottom}}]\} - 8n_F I[Q_F] , \\
I[Q(q; \theta_H)] &= \frac{(kz_L^{-1})^4}{(4\pi)^2} \int_0^\infty dq q^3 \ln\{1 + Q(q; \theta_H)\} , \\
Q_W &= \cos^2 \theta_W Q_Z = \frac{1}{2}Q_S = \frac{1}{2}Q_0[q; \frac{1}{2}] \sin^2 \theta_H , \\
Q_{\text{top}} &= \frac{Q_{\text{bottom}}}{r_t} = \frac{Q_0[q; c_t]}{2(1 + r_t)} \sin^2 \theta_H , \quad Q_F = Q_0[q; c_F] \cos^2 \frac{1}{2}\theta_H , \\
Q_0[q; c] &= \frac{z_L}{q^2 \hat{F}_{c-\frac{1}{2}, c-\frac{1}{2}}(qz_L^{-1}, q) \hat{F}_{c+\frac{1}{2}, c+\frac{1}{2}}(qz_L^{-1}, q)} . \tag{1}
\end{aligned}$$

Here $\hat{F}_{\alpha,\beta}(u, v) = I_\alpha(u)K_\beta(v) - e^{-i(\alpha-\beta)\pi}K_\alpha(u)I_\beta(v)$, where I_α, K_α are modified Bessel functions. ξ is a gauge parameter in the generalized R_ξ gauge introduced in Ref. [22]. The formula for V_{eff} in the $\xi = 1$ gauge without the $I[Q_F]$ term has been given in Refs. [21] and [23]. c_t and c_F are the bulk mass parameters for the top-bottom multiplets and Ψ_F , respectively. $r_t \sim (m_b/m_t)^2$ where m_b and m_t are the masses of the bottom and top quark. $V_{\text{eff}}(-\theta_H) = V_{\text{eff}}(\theta_H)$. Further in the absence of $I[Q_F]$, V_{eff} has symmetry $V_{\text{eff}}(\frac{1}{2}\pi + \theta_H) = V_{\text{eff}}(\frac{1}{2}\pi - \theta_H)$, representing the H parity invariance. The $I[Q_F]$ term breaks this symmetry. The contributions from light quarks and leptons are negligible.

In the pure gauge theory without fermions V_{eff} is minimized at $\theta_H = 0, \pi$ where the EW symmetry remains unbroken. The top quark contribution has minima at $\theta_H = \pm \frac{1}{2}\pi$,

dominating over the gauge field contribution. The fermion Ψ_F shifts the minima toward $\theta_H = 0$. The minimum at $0 < |\theta_H| < \frac{1}{2}\pi$ gives desired phenomenology. The number of the fermion multiplets Ψ_F , n_F , affects the shape of V_{eff} significantly. It will be shown below that the resulting physics, however, is almost independent of n_F . The mass of the Higgs boson, m_H , is given by

$$m_H^2 = \frac{1}{f_H^2} \frac{d^2 V_{\text{eff}}}{d\theta_H^2} \Big|_{\text{min}}, \quad f_H = \frac{2}{g_w} \sqrt{\frac{k}{L(z_L^2 - 1)}} \quad (2)$$

where the second derivative of V_{eff} is evaluated at the minimum of V_{eff} , and g_w is the 4D weak $SU(2)_L$ coupling. The experimental data dictate $m_H \sim 126$ GeV.

The parameters of the model are specified in the following manner. Pick values for n_F and z_L . The parameters, k , two gauge coupling constants associated with $SO(5) \times U(1)$, c_t , r_t , and c_F are self-consistently determined such that at the minimum θ_H of V_{eff} , m_Z , $\sin^2 \theta_W$, $\alpha(m_Z)$, m_t , m_b and $m_H = 126$ GeV are reproduced. We note that all of k , c_t , r_t and c_F implicitly depend on θ_H as well. The KK mass scale is given by $m_{\text{KK}} = \pi k z_L^{-1}$. Hence m_{KK} and θ_H , for instance, are determined as functions of n_F and z_L . $V_{\text{eff}}(\theta_H)$ for $n_F = 3$ and $z_L = 10^7$ is displayed in Fig. 1.

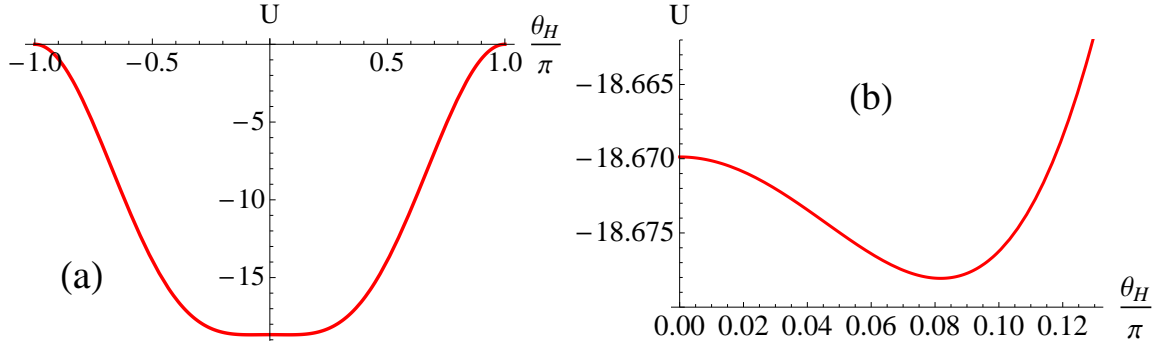


Figure 1: $V_{\text{eff}}(\theta_H)$ for $n_F = 3$, $c_F = 0.353$, $z_L = 10^7$ and $\xi = 1$. $U = (4\pi)^2 (k z_L^{-1})^{-4} V_{\text{eff}}$ is plotted. The minimum is located at $\theta_H = \pm 0.082\pi = \pm 0.258$. (a): $-\pi \leq \theta_H \leq \pi$, (b): $0 \leq \theta_H \leq 0.13\pi$.

The AB phase θ_H is the key parameter in gauge-Higgs unification, which controls the couplings of the Higgs boson to other fields. In Table 1 the values for z_L , θ_H , m_{KK} , k , c_t , c_F , $m_{F(1)}$ and $m_{Z(1)}$ are summarized for $n_F = 3$, where $m_{F(1)}$ is the mass of the lowest mode in the KK tower of Ψ_F and $m_{Z(1)}$ is the mass of the first KK Z boson. As z_L is decreased, θ_H becomes smaller whereas m_{KK} becomes larger. There appears a critical value for z_L below which $m_H = 126$ GeV cannot be realized.

Table 1: Values of the various quantities determined from $m_H = 126$ GeV with given z_L for $n_F = 3$. Universal relations among θ_H , m_{KK} and $m_{Z^{(1)}}$, independent of n_F , are observed. See the text.

z_L	θ_H	m_{KK} (TeV)	k (GeV)	c_t	c_F	$m_{F^{(1)}}$ (TeV)	$m_{Z^{(1)}}$ (TeV)
10^{12}	1.02	1.54	4.90×10^{14}	0.413	0.476	0.155	1.19
10^{11}	0.805	1.75	5.56×10^{13}	0.403	0.454	0.232	1.36
10^{10}	0.632	2.03	6.47×10^{12}	0.391	0.433	0.329	1.59
10^9	0.485	2.45	7.79×10^{11}	0.376	0.411	0.465	1.93
10^8	0.360	3.05	9.72×10^{10}	0.357	0.385	0.668	2.41
10^7	0.258	3.95	1.26×10^{10}	0.330	0.353	0.993	3.15
10^6	0.177	5.30	1.69×10^9	0.296	0.309	1.54	4.25
10^5	0.117	7.29	2.32×10^8	0.227	0.235	2.53	5.91
2×10^4	0.086	9.21	5.87×10^7	0.137	0.127	3.88	7.54

Both θ_H and m_{KK} are physical quantities. They are functions of n_F and z_L . The relation between them are plotted in Fig. 2 for various values of n_F and z_L . As the number of the extra fermions n_F is increased, the location of the minimum of V_{eff} is shifted toward the origin. Nevertheless the relation between θ_H and m_{KK} remains universal. It is approximately given by

$$m_{KK} \sim \frac{1350 \text{ GeV}}{(\sin \theta_H)^{0.787}} , \quad (3)$$

irrespective of n_F and z_L . We note that $m_Z \sim m_{KK} |\sin \theta_H| / (\pi \cos \theta_W \sqrt{kL})$, in which θ_H and $kL = \ln z_L$ are not independent, once m_H is fixed. There must be an underlying reason for the universality relation (3), which remains as a mystery and is left for future investigation. The relation between θ_H and m_{KK} , with $m_{KK} > 3$ TeV for the consistency with low energy data, implies that $\theta_H < 0.3$, which also satisfies the S parameter constraint [20] and the tree-level unitarity constraint [27]. For $\theta_H = 0.1 \sim 0.3$, m_{KK} is predicted to be around $3 \sim 7$ TeV, in a region which can be explored at LHC in the coming years. We have also checked that the m_{KK} - θ_H relation in the $\xi = 0$ gauge is almost the same as in the $\xi = 1$ gauge.

The gauge-Higgs unification model has one parameter, θ_H , to be determined from experiments. With θ_H fixed, all physical quantities are evaluated. By expanding $V_{\text{eff}}(\theta_H + (H/f_H))$ in a power series in H around the minimum, one finds $\lambda_n H^n$ couplings. These couplings λ_3 and λ_4 are plotted in Fig. 3 for $n_F = 1, 3$ and 9. The couplings are smaller than those in the SM. For large $\theta_H > 0.55$, λ_4 becomes negative though V_{eff} is bounded from

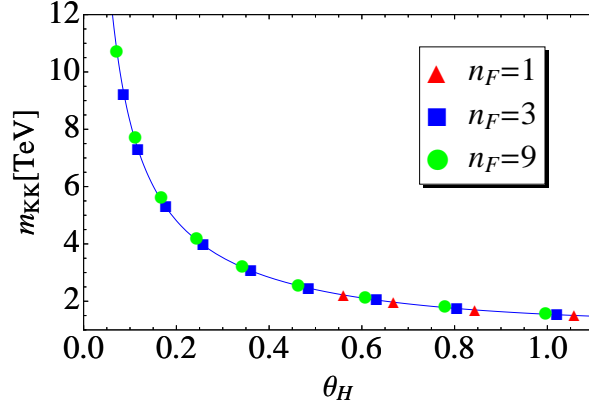


Figure 2: The relation between θ_H and m_{KK} for $\xi = 1$. Triangles, squares, and circles are for $n_F = 1, 3$ and 9 , respectively. The solid curve represents the universal relation (3).

below. It is seen that the relations $\lambda_3(\theta_H)$ and $\lambda_4(\theta_H)$ are also universal and independent of n_F , once $m_H = 126$ GeV is fixed.

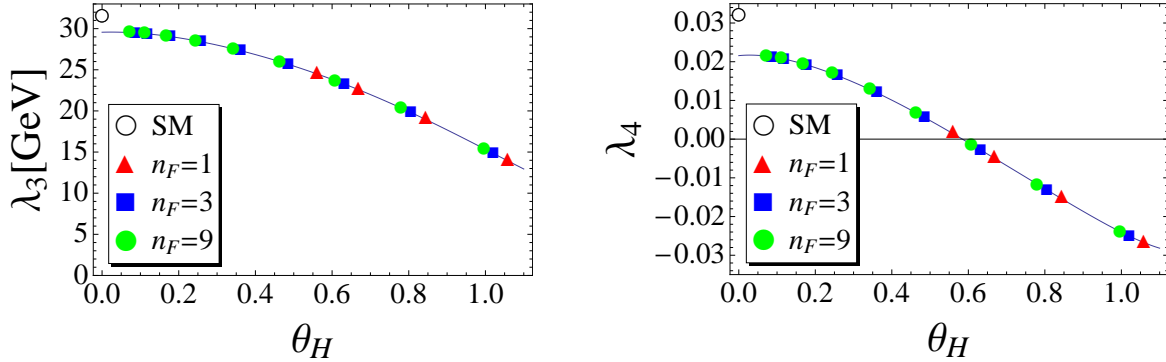


Figure 3: The cubic coupling λ_3 and quartic coupling λ_4 of the Higgs boson are plotted against θ_H for $n_F = 1, 3$ and 9 . The universal relations between (λ_3, λ_4) and θ_H , independent of n_F , are seen. The fitting curves for λ_3 and λ_4 are given by $\lambda_3 = 5.28 + 21.1 \cos \theta_H + 3.20 \cos 2\theta_H$ and $\lambda_4 = 0.0256 - 0.0537 \cos \theta_H + 0.0495 \cos 2\theta_H$, respectively. The SM values are $\lambda_3 = 31.5$ GeV and $\lambda_4 = 0.0320$. [6]

The Higgs couplings to W , Z , quarks/leptons and their KK excited states are determined. All of the 3 point couplings of SM particles to H at the tree level are suppressed by a common factor $\cos \theta_H$. [28]-[31] It is necessary to find these 3 point couplings of KK states for evaluating the 1-loop processes such as $gg \rightarrow H$ and $H \rightarrow \gamma\gamma, gg$.

Let us first consider the process $H \rightarrow \gamma\gamma$. It proceeds through one-loop diagrams. All charged particles with non-vanishing Higgs couplings contribute. The dominant contributions come from the W boson, top quark, and their KK towers. The extra fermion Ψ_F also

contributes. The decay rate is given by [32, 33, 34]

$$\begin{aligned}
\Gamma(H \rightarrow \gamma\gamma) &= \frac{\alpha^2 g_w^2}{1024\pi^3} \frac{m_H^3}{m_W^2} \left| \mathcal{F}_W + \frac{4}{3} \mathcal{F}_{\text{top}} + \left(2(Q_X^{(F)})^2 + \frac{1}{2} \right) n_F \mathcal{F}_F \right|^2, \\
\mathcal{F}_W &= \sum_{n=0}^{\infty} \frac{g_{HW^{(n)}W^{(n)}}}{g_w m_W} \frac{m_W^2}{m_{W^{(n)}}^2} F_1(\tau_{W^{(n)}}), \\
\mathcal{F}_{\text{top}} &= \sum_{n=0}^{\infty} \frac{y_{t^{(n)}}}{y_t^{\text{SM}}} \frac{m_t}{m_{t^{(n)}}} F_{1/2}(\tau_{t^{(n)}}), \\
\mathcal{F}_F &= \sum_{n=1}^{\infty} \frac{y_{F^{(n)}}}{y_t^{\text{SM}}} \frac{m_t}{m_{F^{(n)}}} F_{1/2}(\tau_{F^{(n)}}), \tag{4}
\end{aligned}$$

where $W^{(0)} = W$, $t^{(0)} = t$, $\tau_a = 4m_a^2/m_H^2$ and the functions $F_1(\tau)$ and $F_{1/2}(\tau)$ are defined in Ref. [34]. $Q_X^{(F)}$ is the $U(1)_X$ charge of Ψ_F . y_t^{SM} denotes the top Yukawa coupling in the SM. Note that $F_1(\tau) \rightarrow 7$ and $F_{1/2}(\tau) \rightarrow -\frac{4}{3}$ for $\tau \rightarrow \infty$. The extra fermion multiplet Ψ_F contains particles with electric charges $(Q_X^{(F)} \pm \frac{1}{2})e$. It will be seen below that the contribution \mathcal{F}_F is small for $\theta_H < 0.5$. The $HW^{(n)}W^{(n)\dagger}$ coupling $g_{HW^{(n)}W^{(n)}}$ and the Yukawa couplings $y_{t^{(n)}}$ and $y_{F^{(n)}}$ are unambiguously determined in the gauge-Higgs unification. The infinite sums in (4) turn out finite. The expression for \mathcal{F}_W corresponds to the amplitude in the unitary gauge. It has been shown in Ref. [35] that the correct amplitude is reproduced in the unitary gauge in the SM.

In the gauge-Higgs unification the $HW^{(n)}W^{(n)\dagger}$ and Yukawa couplings result from the $\text{tr } F_{\mu 5} F^{\mu 5}$ term and $\bar{\Psi} \Gamma^5 A_5 \Psi$ terms in the action, where the vector potential A_5 contains the 4D Higgs field. To good approximation $g_{HWW} \sim g_{HWW}^{\text{SM}} \cos \theta_H = g_w m_W \cos \theta_H$ and $y_t \sim y_t^{\text{SM}} \cos \theta_H$.

One finds that

$$\begin{aligned}
I_{W^{(n)}} &= \frac{g_{HW^{(n)}W^{(n)}}}{g_w m_{W^{(n)}} \cos \theta_H} = -\sqrt{kL(z_L^2 - 1)} \frac{\sin \theta_H}{N_{W^{(n)}}} \frac{C(1; \lambda_{W^{(n)}})}{S(1; \lambda_{W^{(n)}})}, \\
N_{W^{(n)}} &= \int_1^{z_L} \frac{dz}{z} \left\{ (1 + \cos^2 \theta_H) C(z; \lambda_{W^{(n)}})^2 + \sin^2 \theta_H \hat{S}(z; \lambda_{W^{(n)}})^2 \right\}, \\
C(z; \lambda) &= \frac{\pi}{2} \lambda z z_L F_{1,0}(\lambda z, \lambda z_L), \\
S(z; \lambda) &= -\frac{\pi}{2} \lambda z F_{1,1}(\lambda z, \lambda z_L), \quad \hat{S}(z; \lambda) = \frac{C(1; \lambda)}{S(1; \lambda)} S(z; \lambda). \tag{5}
\end{aligned}$$

We note that $S(1; \lambda_{W^{(n)}}) = 0$ at $\theta_H = 0$. The values $I_{W^{(n)}}$ are plotted in Fig. 4 for $n_F = 3$ and $\theta_H = 0.360$ ($z_L = 10^8$). One sees that the sign of $I_{W^{(n)}}$ alternates as n increases, and

its magnitude is almost constant; $I_{W^{(n)}} \sim (-1)^n \{0.14 + 0.0025 \ln n + 0.0011 (\ln n)^2\}$ in the range $50 < n < 200$. Note that $|g_{HW^{(n)}W^{(n)}}|$ itself increases with $m_{W^{(n)}}$, in sharp contrast to the behavior in the UED models.[8]

Similar behavior is observed for the Yukawa couplings of the top tower. One finds that

$$I_{t^{(n)}} = \frac{y_{t^{(n)}}}{y_t^{\text{SM}} \cos \theta_H} = -\frac{g_w}{2y_t^{\text{SM}}} \sqrt{kL(z_L^2 - 1)} \frac{\sin \theta_H}{N_{t^{(n)}}} \frac{C_L(1; \lambda_{t^{(n)}}, c_t)}{S_L(1; \lambda_{t^{(n)}}, c_t)},$$

$$N_{t^{(n)}} = \int_1^{z_L} dz \left\{ (1 + \cos^2 \theta_H + 2r_t) C_L(z; \lambda_{t^{(n)}}, c_t)^2 + \sin^2 \theta_H \hat{S}_L(z; \lambda_{t^{(n)}}, c_t)^2 \right\},$$

$$C_L(z; \lambda, c) = \frac{\pi}{2} \lambda \sqrt{z z_L} F_{c+(1/2), c-(1/2)}(\lambda z, \lambda z_L),$$

$$\hat{S}_L(z; \lambda, c) = \frac{C_L(1; \lambda, c)}{S_L(1; \lambda, c)} S_L(z; \lambda, c). \quad (6)$$

The values $I_{t^{(n)}}$ are plotted in Fig. 4. The value of $I_{t^{(n)}}$ alternates in sign as n increases, and the magnitude of $y_{t^{(n)}}$ are almost constant for large n .

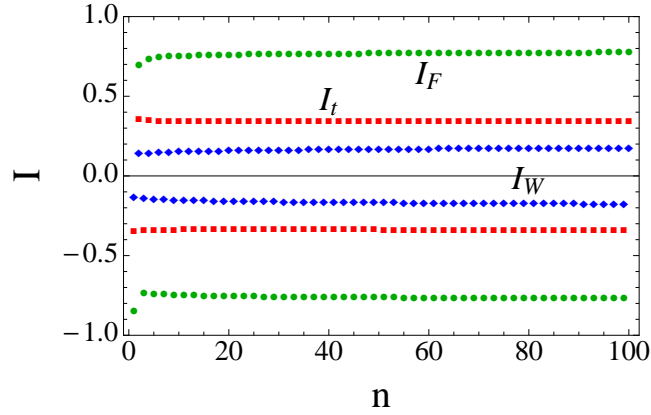


Figure 4: The ratios $I_{W^{(n)}} = g_{HW^{(n)}W^{(n)}}/g_w m_{W^{(n)}} \cos \theta_H$ in (5), $I_{t^{(n)}} = y_{t^{(n)}}/y_t^{\text{SM}} \cos \theta_H$ in (6) and $I_{F^{(n)}} = y_{F^{(n)}}/y_t^{\text{SM}} \sin \frac{1}{2} \theta_H$ in (7) are plotted for $n_F = 3$ and $\theta_H = 0.360$ ($z_L = 10^8$) in the range $1 \leq n \leq 100$. (\square : the top quark tower, \diamond : the W tower, \circ : the Ψ_F tower) $I_{W^{(0)}} = 1.004$ and $I_{t^{(0)}} = 1.012$. The sign of $g_{HW^{(n)}W^{(n)}}$, $y_{t^{(n)}}$ and $y_{F^{(n)}}$ alternates as n increases. $I_{W^{(1)}}, I_{t^{(1)}}, I_{F^{(1)}} < 0$.

The behavior of the $y_{F^{(n)}}$ of the extra fermion is slightly different. In contrast to quarks and leptons, the lowest mode $F^{(1)}$ in the KK tower of Ψ_F is massive at $\theta_H = 0$; its mass is approximately given by $m_{F^{(1)}}(\theta_H) \propto \cos \frac{1}{2} \theta_H$. Its Yukawa coupling is, therefore, expected to be $y_{F^{(1)}} \propto \sin \frac{1}{2} \theta_H$, becoming small for small θ_H . Indeed one finds

$$I_{F^{(n)}} = \frac{y_{F^{(n)}}}{y_t^{\text{SM}} \sin \frac{1}{2} \theta_H} = -\frac{g_w}{4y_t^{\text{SM}}} \sqrt{kL(z_L^2 - 1)} \frac{\cos \frac{1}{2} \theta_H}{N_{F^{(n)}}} \frac{C_R(1; \lambda_{F^{(n)}}, c_F)}{S_R(1; \lambda_{F^{(n)}}, c_F)},$$

$$N_{F^{(n)}} = \int_1^{z_L} dz \left\{ \sin^2 \frac{\theta_H}{2} C_R(z; \lambda_{F^{(n)}}, c_F)^2 + \cos^2 \frac{\theta_H}{2} \hat{S}_R(z; \lambda_{F^{(n)}}, c_F)^2 \right\},$$

$$\hat{S}_R(z; \lambda, c) = \frac{C_R(1; \lambda, c)}{S_R(1; \lambda, c)} S_R(z; \lambda, c). \quad (7)$$

$I_{F^{(n)}}$ is plotted in Fig. 4. Again the value of $y_{F^{(n)}}$ alternates in sign as n increases. For large n , $y_{F^{(n)}}/y_t^{\text{SM}} \sim (-1)^n 0.14$ for $(n_F, z_L) = (3, 10^8)$.

With all these Higgs couplings at hand, one can evaluate the rate $\Gamma(H \rightarrow \gamma\gamma)$ in (4). As all KK masses increase as $m_n \sim \frac{1}{2}n m_{\text{KK}}$ for large n and $F_1, F_{1/2}$ approach constant, the infinite sums rapidly converge as $\sum (-1)^n n^{-1}$ or $\sum (-1)^n n^{-1} (\ln n)^q$ ($q = 1, 2, \dots$). We have found that the sums saturate with about 50 terms. The behavior of the alternating sign in the Higgs couplings of KK states has been previously noticed in Refs. [36] and [37]. Let $\mathcal{F}_{W \text{ only}}$ ($\mathcal{F}_{\text{top only}}$) be the contribution of $W = W^{(0)}$ ($t = t^{(0)}$) to \mathcal{F}_W (\mathcal{F}_{top}) in (4). For $n_F = 3$ and $z_L = 10^8$ (10^5), which yields $\theta_H = 0.360$ (0.117), one finds that $\mathcal{F}_{W \text{ only}} = 7.873$ (8.330), $\mathcal{F}_{\text{top only}} = -1.305$ (-1.372), $\mathcal{F}_W/\mathcal{F}_{W \text{ only}} = 0.998$ (0.9996), $\mathcal{F}_{\text{top}}/\mathcal{F}_{\text{top only}} = 0.990$ (0.998) and $\mathcal{F}_F/\mathcal{F}_{\text{top only}} = -0.033$ (-0.0034).

Let us suppose $Q_X^{(F)} = 0$. In this case we obtain $\mathcal{F}_W + \frac{4}{3}\mathcal{F}_{\text{top}} + \frac{3}{2}\mathcal{F}_F = 6.199$ (6.508). Its ratio to $\mathcal{F}_{W \text{ only}} + \frac{4}{3}\mathcal{F}_{\text{top only}}$ is 1.011 (1.001). In other words, the contributions from KK states and Ψ_F amount to only 1 % (0.1 %). The dominant effect for the decay rates comes from the $\cos \theta_H$ suppression factor in the amplitudes. Compared to the value in the SM, $\Gamma[H \rightarrow \gamma\gamma]$ is suppressed by 10 % (1 %) for $\theta_H = 0.360$ (0.117). The decay rate to two gluons is [38, 39, 40]

$$\Gamma(H \rightarrow gg) = \frac{\alpha_s^2 g_w^2 m_H^3}{128 \pi^3 m_W^2} |\mathcal{F}_{\text{top}}|^2, \quad (8)$$

if Ψ_F is a color singlet. If Ψ_F is a color triplet, \mathcal{F}_{top} is replaced by $\mathcal{F}_{\text{top}} + \frac{2}{3}n_F \mathcal{F}_F$ in the above formula. The correction due to KK excited states is small.

In the gauge-Higgs unification all decay rates for $H \rightarrow WW, ZZ, c\bar{c}, b\bar{b}, \tau\bar{\tau}$ are suppressed by a common factor $\cos^2 \theta_H$ at the tree level. We have found that loop corrections due to KK excited states are very small. Consequently the correction to the branching fraction of $H \rightarrow \gamma\gamma$ turns out very small, about 2% (0.2%) in the gauge-Higgs unification for $\theta_H = 0.360$ (0.117). The observed event rate for $H \rightarrow \gamma\gamma$, for instance, is determined by the product of the Higgs production rate and the branching fraction, $\sigma_H^{\text{prod}} \cdot B(H \rightarrow \gamma\gamma)$. The production rate is suppressed, compared to the SM, by $\cos^2 \theta_H$, but the branching fractions remain nearly the same as in the SM. The gauge-Higgs unification predicts that the signal strength relative to the SM is $\sim \cos^2 \theta_H$. For $\theta_H = 0.1$ (0.3), it is about 0.99

(0.91). This is in sharp contrast to other models. In the UED models the contributions of KK states to \mathcal{F}_{top} add up in the same sign and may become sizable.[8] In the gauge-Higgs unification the contributions alternate in sign in the amplitudes, resulting in the destructive interference and giving very small correction.

The rate $\Gamma(H \rightarrow \gamma\gamma)$ in Eq. (4) can be enhanced through the factor $2(Q_X^{(F)})^2 + \frac{1}{2}$ for sufficiently large $Q_X^{(F)}$. For example, for $Q_X^{(F)} = 4$ and $n_F = 3$, we obtain the enhancement by a factor 2.22 (1.13) compared with the SM.

The fact $m_H \sim 126$ GeV leads to important consequences in the gauge-Higgs unification. We have found the universal relations among m_{KK} , λ_3 , λ_4 and θ_H , which are independent of how many extra fermions are introduced. The low energy data, the S parameter constraint, and the tree-level unitarity constraint indicate small $\theta_H < 0.3$. The KK mass scale m_{KK} is predicted to be $3 \sim 7$ TeV for $\theta_H = 0.1 \sim 0.3$. The existence of new charged heavy particles can affect the production and decay rates of the Higgs boson through loop diagrams. There are many proposals of models which employ such a mechanism to predict the enhancement of the $H \rightarrow \gamma\gamma$ mode over other decay channels.[8]-[16] In the gauge-Higgs unification there are new charged heavy particles, namely KK excited states of W and top quark. However, we have shown that their couplings to the Higgs boson alternate in sign in each KK tower so that the correction to the decay and production rates becomes very small. The gauge-Higgs unification gives phenomenology at low energies very close to that of the SM so long as $Q_X^{(F)}$ is moderately small.

Nevertheless new rich structure is predicted to emerge. We have seen above that the cubic and quartic self-couplings of the Higgs boson significantly deviate from the SM. The most clear signal for the gauge-Higgs unification would be the production of the first KK states of the Z boson and photon at LHC. Their masses are predicted, for $\theta_H = 0.117$ (0.360), to be $m_{Z(1)} = 5.910$ (2.414) TeV and $m_{\gamma(1)} = 5.913$ (2.421) TeV. The current data [41]-[44] indicate $m_{Z(1)} > 2.5$ TeV. We have checked that there is a universal relation between θ_H and $m_{Z(1)}$, independent of n_F . The data therefore imply that $\theta_H < 0.35$. Another robust signal would be the production of a pair of the first KK state of the extra fermion, $F^{(1)}\bar{F}^{(1)}$, which become stable. So far no new exotic stable charged fermion has been observed at LHC.[45] Its current limit puts a constraint $m_{F(1)} > 0.5$ TeV. The value of $m_{F(1)}$ depends on both θ_H and n_F so that no universal relation between $m_{F(1)}$ and θ_H is found. $m_{F(1)}$ becomes smaller as n_F increases with θ_H fixed. $m_{F(1)} > 0.5$ TeV implies $\theta_H < 0.45$ for $n_F = 3$. We will come back to these issues with more details separately.

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